ONE-CENTIMETER ORBITS IN NEAR-REAL TIME: THE GPS EXPERIENCE ON OSTM/JASON-2

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The advances in Precise Orbit Determination (POD) over the past three decades have been driven in large measure by the increasing demands of satellite altimetry missions. Since the launch of Seasat in 1978, both tracking-system technologies and orbit modeling capabilities have evolved considerably. The latest in a series of precise (TOPEX-class) altimeter missions is the Ocean Surface Topography Mission (OSTM, also Jason-2). GPS-based orbit solutions for this mission are accurate to 1-cm (radial RMS) within 3-5 hrs of real time. These GPS-based orbit products provide the basis for a near-real time sea-surface height product that supports increasingly diverse applications of operational oceanography and climate forecasting.

INTRODUCTION

Over the past 30 years, the practice of Precise Orbit Determination (POD) has witnessed remarkable advances in both satellite-tracking technologies and modeling skill.[1] Many of these advances have been driven by the demands of satellite radar altimetry missions,[2] because radial orbit errors map directly and fully into altimetric measurements of sea-surface height (SSH). Small variations in the SSH, when observed over sufficiently great distances, can be symptomatic of important climate-scale changes in the ocean currents. Orbit errors tend to manifest at very long wavelengths (centered on the orbital period), making them conspicuously damaging to measurements of ocean circulation from satellite altimetry.

The formidable challenge to the POD community was underscored with the launch of the Seasat mission in 1978.[3] The goal of the Seasat POD experiment was to develop and refine the methodology to compute the altitude of the satellite to an accuracy equal to the 10-cm precision of the altimeter range measurement.[4] Initial orbit computations undertaken with the Seasat data yielded radial accuracies of only 3–5 m. Subsequent tailoring of the Earth gravity model reduced this to < 1 m,[5] but still an order of magnitude larger than the precision of the radar altimeter.

The Seasat experience provided the impetus for a dedicated, long-term POD initiative, the centerpiece of which was an effort to continuously improve the model of the geopotential.[6] Also included in this initiative were programs to enhance or better exploit the abundance, diversity and accuracy of satellite tracking data,[7, 8] and to address deficiencies in models of other (e.g., non-conservative) forces underlying satellite motion.[9]

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The main beneficiary of this initiative was the joint U.S./France TOPEX/POSEIDON (T/P) mission, launched in 1992.[10] The first mission dedicated to observing the large-scale patterns of circulation that bear on the understanding of climate, T/P had a 13-cm requirement for the radial (RMS) accuracy of the orbit solutions. The satellite carried three dedicated POD payloads: 1) a laser retro-reflector array (LRA) serving as a target for satellite laser ranging (SLR) observatories; 2) a Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) receiver provided by the French Space Agency, CNES; and 3) a GPS Demonstration Receiver (GPSDR) supplied by NASA. Early orbit solutions for T/P were accurate to 3–4 cm (RMS) in the radial component, and represented a significant improvement over the mission objectives.[11, 12, 13] This accomplishment testified to the success of the long-lead time gravity model improvement effort, and to the robustness of the tracking systems and solution strategies designed to best exploit them.

Advances in gravity modeling have continued, notably using data from the Gravity Recovery and Climate Experiment (GRACE).[14] Gravity fields derived from GRACE have nearly eliminated the static component of the geopotential model as a source of error in T/P POD. While the T/P mission ended in 2005, POD techniques continue to evolve, and the RMS radial accuracy of current T/P orbit solutions is estimated at better than 2 cm.[15]

Jason-1 and OSTM/Jason-2—the successors to T/P—have enjoyed the benefit of even higher POD accuracies. Improvements to the GPS, DORIS, and SLR systems bear significant responsibility for this, as do ongoing advances in modeling. Owing to the 3-D, continuous nature of GPS data, these tracking observations have proven particularly powerful. By capitalizing on data from the BlackJack GPS receiver carried on the Jason-1 mission (2001–pr.), POD investigators were able to reduce the RMS radial orbit error to the level of 1-cm.[16, 17, 18] These solutions rely significantly on continuous, precise monitoring of the GPS carrier phase from up to 12 GPS satellites simultaneously. The geometric strength of the GPS data promotes greater liberation of the POD strategy from the models of the forces underlying the satellite motion. Resolving the integer ambiguities on the GPS carrier-phase measurements enables even higher accuracies.[19, 20, 21] Radial orbit errors for the Ocean Surface Topography (OSTM)/Jason-2 mission (2008–pr.) may now be smaller than 1 cm (RMS).[22] At this level of error, it is quite challenging to provide a true test of accuracy, even using withheld data (such as SLR, in the case of a GPS-based orbit.)

With the overall success of the T/P and Jason series of missions, a new requirement on POD for radar altimeter missions has emerged. Operational oceanographic applications of the data have blossomed, as the altimeter measurements have been disseminated with latencies closer and closer to real time. Near-real-time (NRT) orbit solutions for T/P were first produced in the 1990s.[23, 24, 25] Next-day GPS-based orbit solutions for T/P supported a number of diverse operational applications,[26, 27] and figured positively in the early prediction of the historic 1997-98 El Niño event by the National Center for Environmental Prediction.[28]

To address emerging operational applications of altimetry, Jason-1 carried a DORIS-based system called DIODE to support real-time (onboard) POD.[29] Advances in NRT processing of GPS data also continued, and spurred the development of a research-grade NRT SSH product for Jason-1. This product featured GPS-based orbit solutions accurate to better than 2.5 cm (radial RMS) with latencies of only 3–5 hr.[30] These products were used in many operational applications: among the most publicized examples were hurricane intensity forecasts for Hurricanes Katrina and Rita on approach to the U. S. Gulf Coast.[31]

The drive for ever-higher POD accuracies and shorter latencies has culminated in the OSTM/Jason-2 mission. After a recent upload, the updated DIODE system is supporting real-time on-board POD with accuracies of 3–4 cm (radial RMS).[32] These DIODE orbit solutions provide the basis for an Operational Geophysical Data Record (OGDR) available within 1-3 hr of real time.[33] Meanwhile, improvements to the NRT GPS processing have enabled the achievement of 1-cm accuracies (radial RMS) with typical latencies shorter than 4 hrs.[34, 35] These orbit solutions provide the basis for producing a NRT SSH product with latencies only slightly longer (~1.5 hr) then the corresponding OGDR. In this paper, we describe the elements of the GPS-based POD system that supports these achievements, and discuss the challenges of validating a 1-cm accurate orbit.

ELEMENTS OF THE NEAR REAL TIME GPS-BASED POD SYTEM

Flight Receiver System

The cornerstone of the GPS POD system on OSTM/Jason-2 is the flight receiver (Figure 1). Built by General Dynamics and based on the JPL "BlackJack" design, the receiver features 48 hardware channels. The receiver is capable of tracking code (pseudorange) and carrier on the P1, P2 and CA signals from up to 16 GPS satellites simultaneously. As currently configured in orbit, the OSTM/Jason-2 receiver tracks up to 12 satellites, which represents everything in view to either one of the topside antennas virtually all of the time. This "all-in-view" tracking philosophy is important for the most demanding POD applications, because it insures the best possible tracking geometry and guarantees the receiver will not have to break track on one satellite to select another. Most of the strength for cm-level POD comes from the continuity of the carrier-phase measurements. Satellite selection algorithms can actually compromise POD, since the tracking passes are abbreviated in exchange for better geometry.

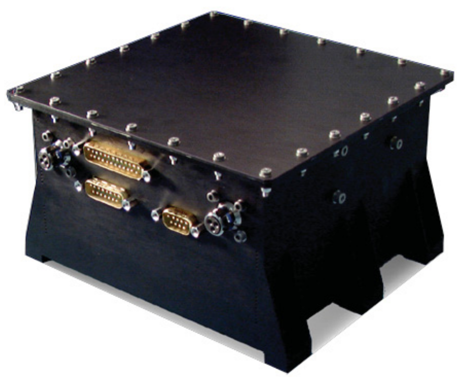

Figure 1. The BlackJack GPS Payload (GPSP) Receiver on OSTM/Jason-2.

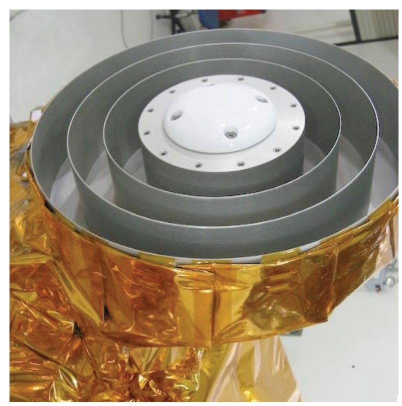

Figure 2. The BlackJack GPS Payload (GPSP) Antenna on OSTM/Jason-2.

BlackJack receivers have been carried on several scientific missions on which NASA has partnered, including the Shuttle Radar Topography Mission, Jason-1, Champ, SAC-C and GRACE. The BlackJack receiver is not "keyed", i.e., it does not contain a Selective Availability/Anti-Spoofing module (SAASM). Instead, the receiver uses advanced codeless tracking techniques to obtain precise GPS observations on both current GPS frequencies (L1, L2) without knowledge of the encrypted Y code.[36]

The BlackJack receiver design philosophy was to advance new technology for POD, and to do this at low cost. This philosophy carries the implication that many of the parts are not available in a radiation-hardened form. As a consequence, system resets were designed into the autonomous receiver operations as a means of clearing soft-bit errors induced by cosmic rays and the occasional latch-up condition. At the 1300 km altitude of the OSTM mission, where the radiation environment is severe, data gaps due to resets and other losses of lock may occur multiple times per day, almost exclusively over the South Atlantic Anomaly. They are typically short in duration (e.g., 1-5 min), however, and the receiver recovers autonomously. These gaps do, however, cause breaks in the accumulated carrier-phase measurements. This implies the POD solution cannot be overly aggressive in its reliance on the tracking data over the force models.

Another critical element of the GPS flight system is the omni-directional choke-ring antenna (Figure 2). Originating at JPL in the 1980s,[37] the overall design helps to suppress multipath and has been proven on both the T/P and Jason-1 altimeter missions. OSTM/Jason-2 carries dual receiver-antenna strings for cold redundancy.

Data collected by the GPS receiver are transmitted through a serial (1553) data bus on the spacecraft, and telemetered along with other science and engineering data to Earth terminals when they are in view of the spacecraft. With ground terminals in Aussaguel, France, and Poker Flat, U. S. (Alaska) plus a backup site at Wallops Island, U. S. (Virginia), one telemetry contact every 1.5 to 2.5 hr is typical. The availability of the GPS telemetry from the mission is the limiting factor in producing accurate, short-latency GPS-based estimates of the orbital height for use in operational oceanographic applications. The same limitation, of course, applies to telemetry from all the science sensors (e.g., altimeter, radiometer) on the satellite.

Ground GPS System

Accurate, short-latency estimates of the GPS satellite orbits and clock offsets are needed for NRT POD. The information broadcast by the GPS satellites themselves is typically accurate to a few meters, and is not adequate for cm-level POD. The NASA Global Differential GPS System (GDGPS) provides the framework needed for accurate POD and other demanding real-time GPS applications. GDGPS is a complete, highly accurate, and robust real-time GPS monitoring and augmentation system.[38] Relying on a large (~100-station) ground network of real-time reference receivers, robust network architecture, and real-time processing software, the GDGPS System produces estimates of the GPS orbits and clock offsets that are accurate to 20 cm (< 1 nsec) within 5 s of real time, along with integrity information (Figure 3). The GDGPS software and operations concept will provide the basis for the navigation component of the Next-Generation GPS Control Segment (OCX), currently under development for the U. S. Air Force by Raytheon Corporation, partnering with JPL.[39]

Following the model used for Jason-1, we initially adopted the real-time (RT) GDGPS orbits and clock offsets as the framework for the OSTM/Jason-2 NRT POD solutions. RT orbits and clocks, however, are not strictly necessary, since the latency of the OGDR products (1-3 hr after acquisition) are driven by the availability of the telemetry and subsequent altimeter processing. We have recently started issuing a new Ultra-Rapid (UR) GPS constellation (orbit and clock-offset) product that offers higher accuracies than the GDGPS solutions, but with a longer latency (1 hr).[40] The extra latency enables the use of backward smoothing in a batch process. The process initiates every hour using a 24-hr moving window of tracking observations from a global 40-station network. A priori orbits come from the RT (GDGPS) solutions. The resulting UR GPS constellation products (orbit and clock offsets) are accurate to 5 cm (3D) in the terrestrial reference frame.

The UR process also issues specialized GPS phase-bias combinations from the network called widelanes. These widelane phase biases can be used—together with the precise orbit and clock offset information—to resolve the integer ambiguities of the carrier phase from an individual receiver. [21] Widelane phase biases are now produced routinely for all of JPL's GPS constellation products, except for the RT (GDGPS) solutions. Use of widelane information to resolve phase ambiguities for the BlackJack receiver on OSTM/Jason-2 has markedly improved the precise orbit solutions. [22]

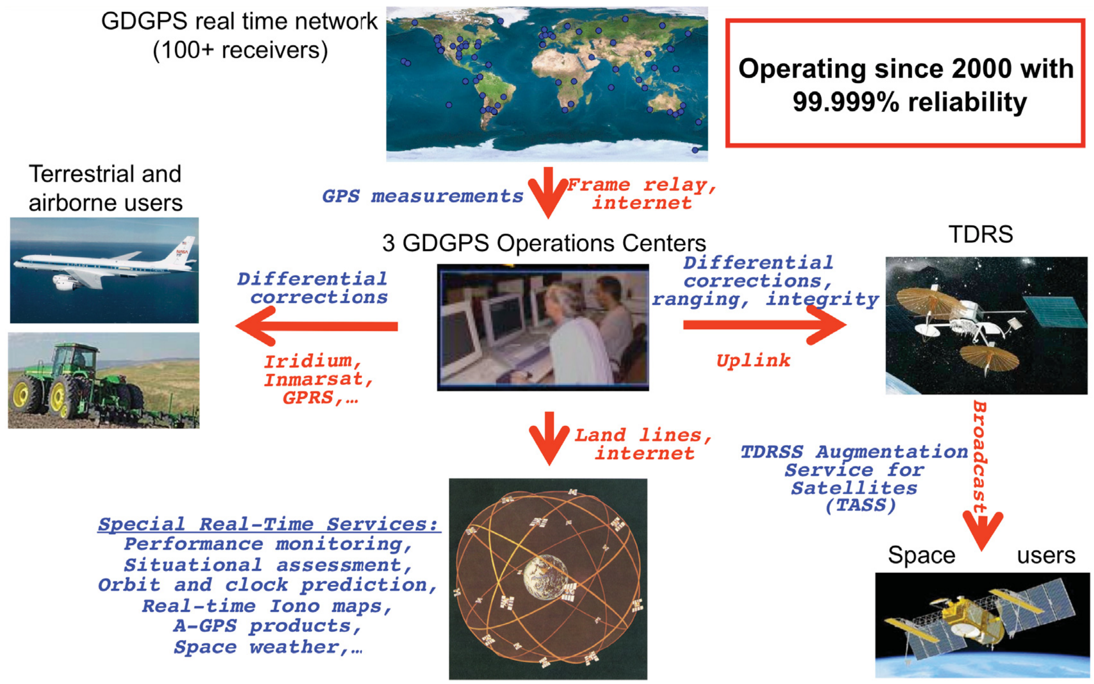

Figure 3. Conceptual Depiction of NASA GDGPS System

OSTM/Jason-2 POD System

The accurate UR GPS constellation products (orbits and clock offsets) provide the underpinning for exploiting the Jason-2 GPS tracking measurements in near-real time. This is not sufficient, however, to support computation of the Jason-2 orbit at the 1-cm level. Accurate models of the forces underlying the motion of the satellite are still needed, as are high-fidelity spacecraft-specific models of measurement effects, such as phase multipath. Bertiger *et al.*[22] provide a full accounting of the current Jason-2 POD strategy used at JPL, and the details are not repeated herein. Many of the elements of the strategy follow the standards used by CNES to produce the definitive orbit solutions for the GDR (climate-quality data record).[41] The model for the static geopotential is from the GRACE mission,[42] and solar radiation pressure is treated using a custom s/c model based on engineering drawings and surface properties. Critical to the accurate modeling of the surface forces, such as solar radiation pressure, is information on the Jason-2 s/c attitude. This information is provided in the form of quaternion data, which comes in the telemetry stream from the s/c along with the GPS tracking data. The attitude data are also essential for reconciling the location of the GPS (choke-ring) antenna on Jason-2 with the s/c center of mass to which the POD solution is referred.

At the foundation of the automated software for performing the NRT POD for Jason-2 is the JPL GIPSY software.[43] Customized scripts to manage the input and output data and validate the orbits surround the GIPSY package. Details of the NRT processing sequence are provided elsewhere,[34, 35] and we repeat only the salient features herein.

The overall process is triggered by the arrival of the telemetry packets (approximately every two hours) containing the GPS tracking data. A moving 24-hr window of tracking data, ending with the last observation in the current telemetry dump, is maintained and processed in a batch mode, using both forward-filtering and backward smoothing. The filtering strategy includes a final reduced-dynamic iteration, wherein empirical accelerations are estimated as stochastic processes that explain small departures of the true orbital path from the converged dynamic solution.[44] Due to the high fidelity of the force models for OSTM/Jason-2, these accelerations are tightly constrained, and are represented as harmonics at the resonant frequency of 1 cycle-per-revolution (1 cpr).[22] The batch process consumes only a few minutes of CPU time after the telemetry dump is received.

The OSTM/Jason-1 NRT orbit solutions are patched together using extracts from consecutive batch processes, triggered by the arrival of each telemetry dump (Figure 4). Due to filter-edge effects, which degrade the orbit accuracies at the extremes of each 24-hr solution, we maintain a buffer of one hour measured back from the end of the solution. This is achieved by waiting for the delivery of telemetry dump N+1 before delivering the orbit for telemetry dump N. While this increases the POD latency by approximately two hours, it represents only an additional hour beyond the typical SSH production (i.e., the OGDR release for telemetry dump N) due to the overhead on the altimetry processing.

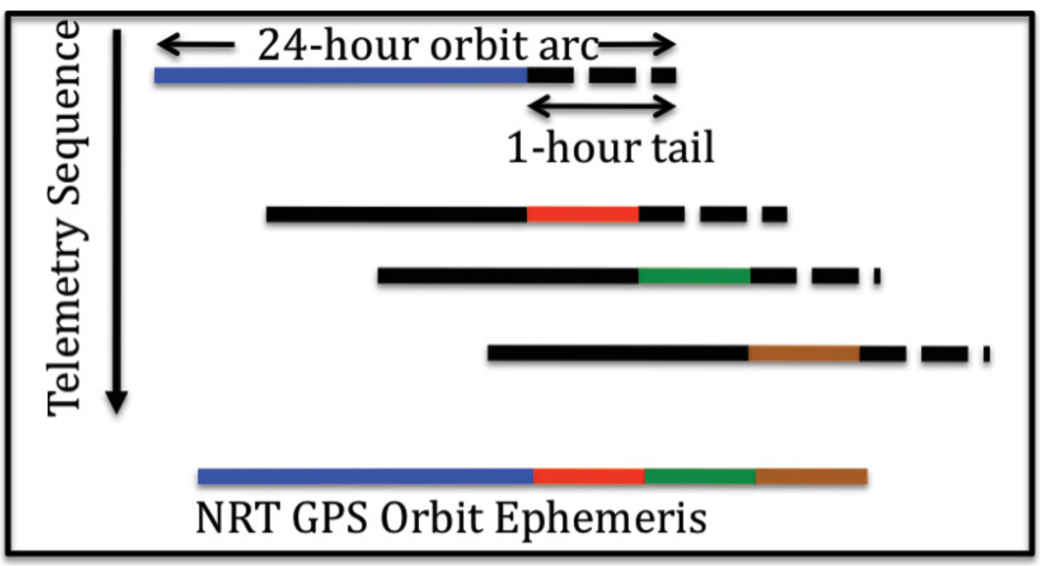

Figure 4. Schematic of OSTM/Jason-2 NRT POD sequence.

Verification System

A comprehensive verification of the Jason-2 NRT orbits as a prerequisite to release is not practical. This, however, is consistent with the intent of the NRT SSH products.[34] They are considered operational research-grade data products, and are subject to only very basic verification. In the case of the POD process, for example, there are measures in place to automatically block release of the orbit solutions given prior knowledge of s/c maneuvers. Beyond that, statistics on the orbit consistency (dynamic vs RD), fit residuals and other radiometric quantities are automatically compiled and accumulated for ongoing review. Retrospective analyses are used to continuously improve the orbits and assess the accuracy after the fact.

Figure 5 depicts, for the last three months, a time series of the fit residuals, and the internal orbit differences (RMS, dynamic vs RD) in the radial component. Most of the strength for the POD solutions is derived from the carrier phase data (LC), for which the fit to the model is typically 8 mm. The pseudorange data (PC) have a much larger misfit (median of 26 cm) due to multipath on the GPS code measurements. They remain valuable, however, for leveling the phase biases and the solution for the clock offset of the receiver. The orbit differences (dynamic vs RD) are measures of consistency, and are useful for diagnosing problems with the data and/or modeling.

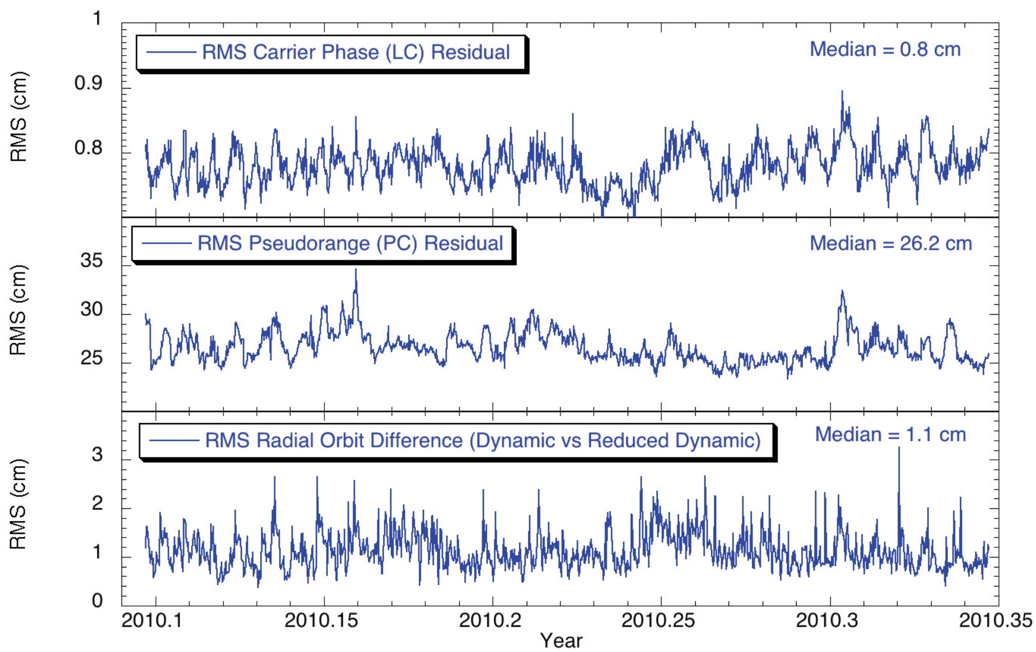

Figure 5. Radiometric Statistics for Jason-2 NRT Orbits. The data have been extracted from the automated POD system and correspond to the last 3 months (thru May 7, 2010).

THE 1-CM ORBIT: HOW DO WE KNOW?

Validating orbit accuracies at the 1-cm level is very challenging. The most powerful tests use independently determined orbit solutions, and withheld data (notably SLR, since the best ground-based observatories provide an unambiguous cm-level measure of the range to the satellite). We highlight here two of the most compelling lines of evidence that the NRT orbits for OSTM/Jason-2 are accurate to 1 cm (radial RMS). Results from additional tests directed at assessing the accuracy of the GPS-based NRT orbits for OSTM/Jason-2 are provided elsewhere.[34, 35]

Depicted in Figure 6 is a long-term time series of the radial differences of the NRT orbits with respect to a precise post-processed solution from the Goddard Space Flight Center (GSFC).[15] The GSFC solution is based on SLR and DORIS only, and uses a different software package (GEODYN). As with our GPS NRT solutions, the GSFC solution used a reduced-dynamic (RD) approach to decrease dependence on errors in the force models (some of which are common to both the GSFC and JPL strategies due to standardization[41]). The RD solutions from GSFC will be steered away from the GEODYN dynamic solution by the combined SLR/DORIS data, while the NRT orbit solutions will be steered away from the GIPSY dynamic solution by the independent GPS data. The differences of the two RD orbit solutions should provide a better measure of the relative accuracy than the corresponding dynamic orbit solutions, even though both use independent tracking data. Taken over the 230 days, the differences indicate that the orbit solutions agree to 0.9 cm (RMS) in the radial component.

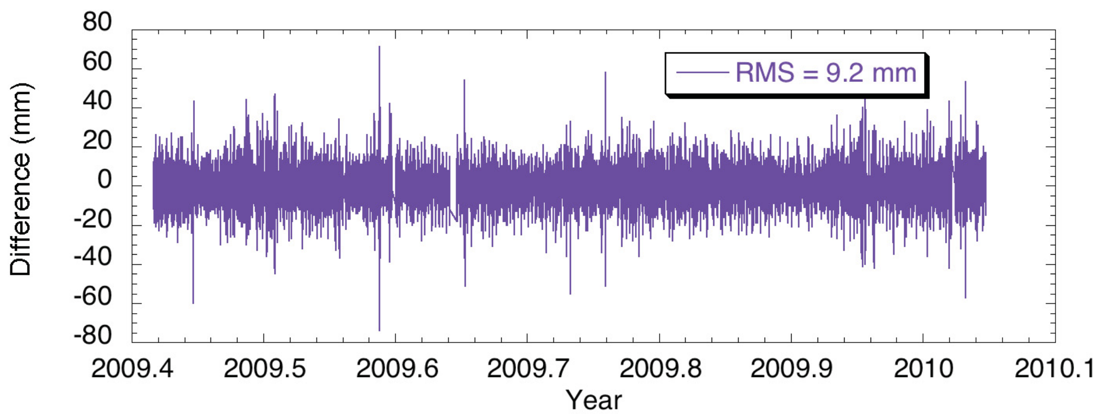

Figure 6. OSTMJason-2 Radial Orbit Differences: GPS-based NRT solution (GIPSY/JPL) vs. SLR/DORIS (GEODYN/GSFC). The difference is taken over 230 days, and illustrates that the two solutions based on independent data agree to better than 1 cm.

In one of the most powerful tests of radial orbit accuracy, SLR observations of the OSTM/Jason-2 satellite can be used to independently assess the accuracy of the GPS-based NRT orbits. In this test, SLR data are not allowed to influence the orbit solution. The NRT orbits determined from the BlackJack data are held fixed, and the SLR data are passed through the solution to determine the level of mismatch between the laser ranges and the orbit. The analysis is restricted to high-elevation passes (greater than 60º as observed from the laser observatory), in order to better isolate the radial component of the orbit error. For each pass over a laser site, a range bias is determined using laser range observations made above 60º. In this case, data from four high-quality SLR observatories that frequently tracked OSTM/Jason-2 were considered. Figure 7 provides a time series of the range biases over 183 days in 2009.

The repeatability of the SLR range biases falls between 7 and 11 mm, depending on the station. The overall RMS of the SLR range biases across all stations (4) and passes (133) is 14 mm. This figure represents the combined effects of radial errors in the NRT orbit, as well as noise and station-dependent biases in the SLR data. At this level of fit, station-coordinate errors and unmodeled crustal deformations (e.g., atmospheric loading) also influence the results. The overall result is consistent with radial orbit accuracies at the level of 1 cm in an RMS sense.

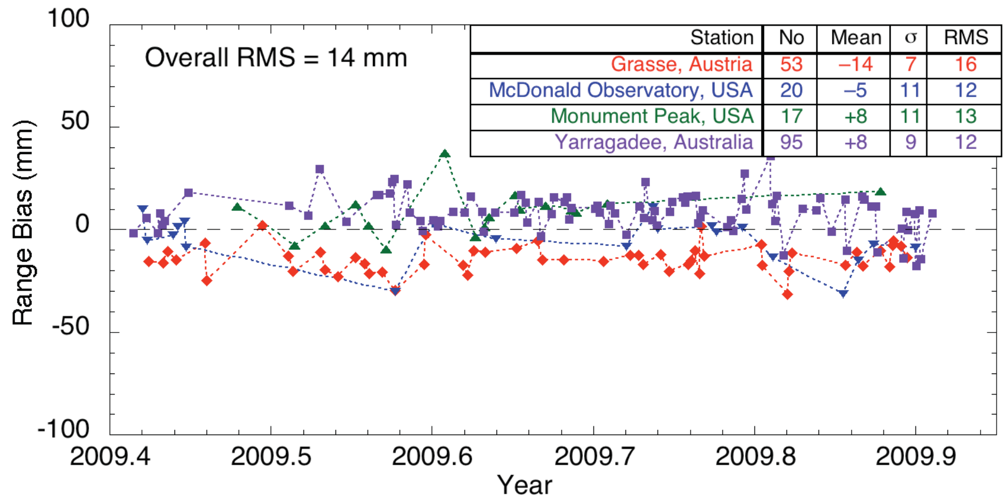

Figure 7. Misfit between GPS-based NRT orbit solutions and high-elevation laser range biases over 183 days in late 2009. Each point represents a range bias computed over a single high-elevation (> 60˚) pass. The statistics are accumulated for each of four stations.

APPLICATION: SEA-SURFACE HEIGHT

The GPS-based NRT orbit solutions for OSTM/Jason-2 are used to produce a value-added SSH product to support a wide variety operational oceanographic applications. The NRT SSH product corresponding to each telemetry pass is released. The latency of the data with respect to the time of acquisition by the satellite is typically 3-5 hrs, depending on time registration of the data within the pass and the time elapsed since the last telemetry dump. The resolution of the SSH data is about 6 km along the satellite ground track (1-Hz sampling), and the accuracy is better than 4 cm (RMS).[34]

Launched in 2001, the Jason-1 mission is still operating nearly four years beyond the end of its prime mission. In January 2009, after the verification phase of OSTM/Jason-2, Jason-1 was moved to an orbit that produces an interleaving ground track with its successor. This effectively doubles the spatio-temporal resolution of the SSH measurements, enabling improved monitoring of shorter-wavelength (e.g., mesoscale) ocean features. Unfortunately, both Jason-1 GPS receivers were deemed inoperable by April 2009 due to cumulative radiation effects.

While there are no current GPS data from Jason-1 to support precise NRT POD, the NRT SSH differences (Jason-1 vs. Jason-2) at ground-track crossing locations (crossovers) can still be used to generate NRT orbit altitudes for Jason-1.[34] This procedure begins with lower-accuracy Jason-1

SSH measurements based on a dynamically filtered/smoothed version of the on-board (DIODE) orbit solutions. These NRT SSH measurements are reconciled with the more accurate Jason-2 NRT measurements at crossover locations by adjusting for Jason-1 orbit errors at the satellite resonance frequency (1 cpr). The 1-cm-quality Jason-2 orbit solutions thus serve as the foundation for accurate NRT SSH measurements from not only Jason-2, but also its predecessor, Jason-1.

Shown in Figure 8 are maps of SSH anomalies based on actual NRT data from both Jason-1 and Jason-2, as well as the combined missions. The data show the climatic state of the ocean for the period April 12, 2010, to April 23, 2010. The results from the two missions are nearly indistinguishable from one another, testifying to the efficacy of the method for improving the Jason-1 NRT SSH data by capitalizing on the accurate GPS-based SSH estimates for Jason-2. The combined NRT SSH products support wide-ranging operational applications of satellite altimetry that demand short-latency information of sea level and ocean circulation.

CONCLUSION

New GPS-based precise orbit determination (POD) strategies have enabled us to reach 1-cm accuracy (RMS) in determining the radial component of the OSTM/Jason-2 satellite within 4 hr of real time. This has important implications for both climate and ocean circulation studies, as well as operations oceanography, owing to the conspicuous ability of orbit error to confound estimates of ocean circulation.[2] What makes orbit error so troublesome is its tendency to express itself systematically over many thousands of km, mimicking patterns of large-scale ocean currents. Reducing the radial orbit error to the 1-cm level in near real time represents an important advancement in the field of satellite altimetry.

Leveraging off of these 1-cm OSTM/Jason-2 orbits, we are able to produce accurate sea surface height (SSH) measurements in near-real time for both the OSTM/Jason-2 and Jason-1 missions. These data products have wide-ranging benefits to forecasting, operational oceanography and natural-hazards monitoring.

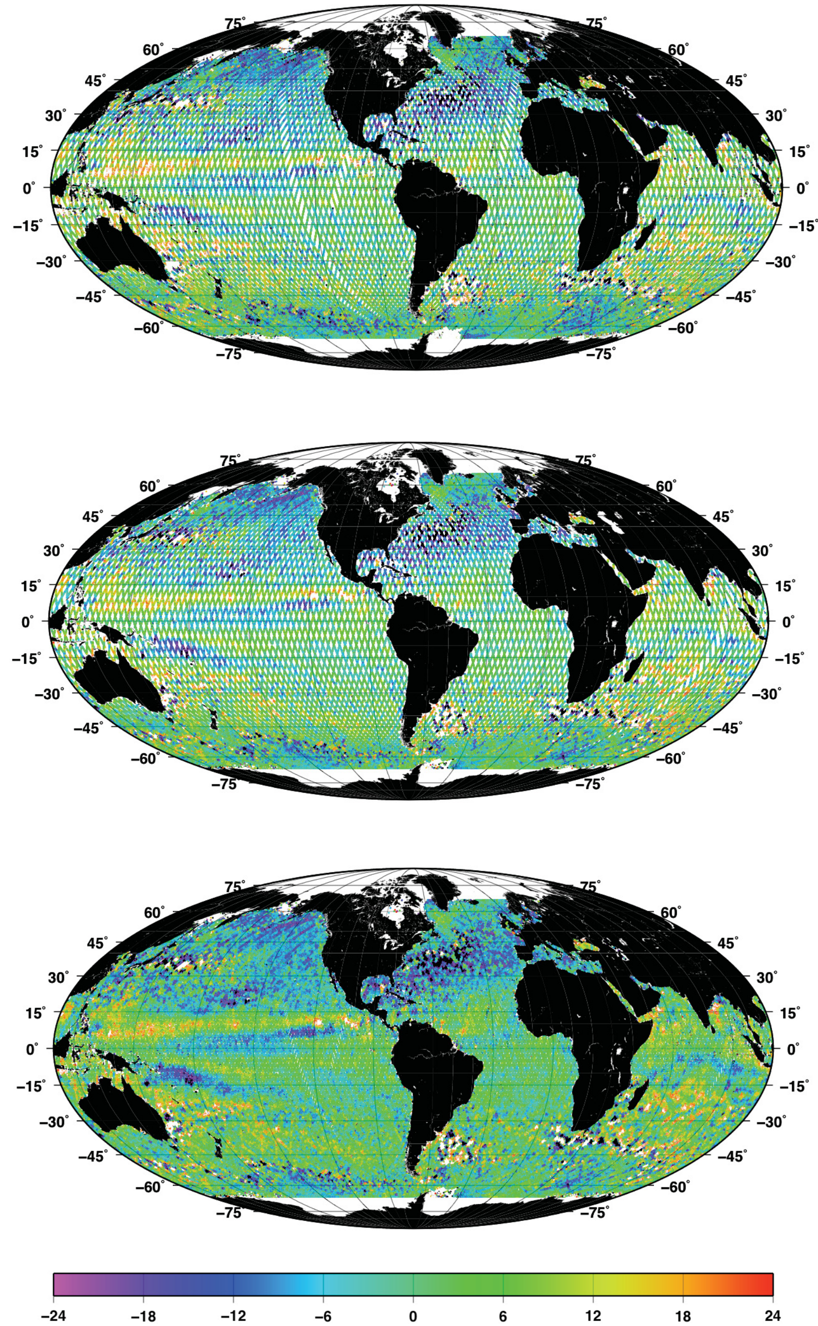

Figure 8. Sea-surface height anomaly (cm) for April 12–23, 2010, based on near-real-time (3-5 hr latency) altimeter data. Top: Jason-1; Middle: OSTM/Jason-2; Bottom: Combined missions. At the foundation of all SSH estimates is the GPS-based orbit solution for Jason-2, accurate to 1-cm in a radial RMS sense.

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